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Innovative Applications of O.R.

Parallel evolution and response decision method for public sentiment based on system dynamics

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A B S T R A C T

Governments face difficulties in policy making in many areas such as health, food safety, and large-scale projects where public perceptions can be misplaced. For example, the adoption of the MMR vaccine has been opposed due to the publicity indicating an erroneous link between the vaccine and autism. This research proposes the "Parallel Evolution and Response Decision Framework for Public Sentiments" as a real-time decision-making method to simulate and control the public sentiment evolution mechanisms. This framework is based on the theories of Parallel Control and Management (PCM) and System Dynamics (SD) and includes four iterative steps: namely, SD modelling, simulating, optimizing, and controlling. A concrete case of an anti-nuclear mass incident that sparked public sentiment in China is introduced as a study sample to test the effectiveness of the proposed method. In addition, the results indicate the effects by adjusting the key control variables of response strategies. These variables include response time, response capacity, and transparency of the government regarding public sentiment. Furthermore, the advantages and disadvantages of the proposed method will be analyzed to determine how it can be used by policy makers in predicting public opinion and offering effective response strategies.

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1. Introduction

Social Networking Services (SNS) such as MicroBlog and WeChat have become the most prominent carriers and tools for disseminating public sentiment. Public sentiment reflects the ideas, attitudes, opinions and emotions that people express on certain noticed issues. Positive public sentiment is often a necessary prerequisite for political action, and vice versa; negative public sentiment may become a major obstacle for a correct decision (Burstein, 2010). In this situation, public sentiment plays an increasingly important role in policy making processes in many areas such as public health, food safety, and large-scale projects where public perceptions can be misplaced (Jiang, Lin & Qiang, 2016). Typical examples include incidents like "the adoption of the MMR vaccine has been opposed due to the publicity indicating an erroneous link between the vaccine and autism" (Godlee, Smith & Marcovitch, 2011), "China's milk powder industry had seriously declined due to the public sentiment of the Sanlu milk powder incident" (Chen, 2009),

"5 G mobile phone masts have been vandalised caused by a false link with the coronavirus", and "Nuclear fuel processing project has been cancelled because of an anti-nuclear public sentiment in Guangdong province of China" (Li, Guimin, Jing, Dai & Tian, 2015).

Lacking relevant popular science knowledge, most people never say 'yes' to any large-scale project or product involved in a public sentiment. In addition, as long as the projects are planned or "fears" are turned into "crisis", negative public sentiment will be sparked immediately (Lee & Chun, 2016; Xiong, Liu & Cheng, 2017). Worse yet, if public sentiment is not guided and controlled in time, its effects will spread from the virtual network to the physical world and cause further secondary disasters, such as mass incidents. The interdisciplinary online-offline effects which make the situation more complex and uncertain, acutely threaten social stability and national economic development.

1.1. Bottlenecks of related works

There have been significant studies of public sentiment triggered by different incidents. In the public health areas, several epidemiologic studies found that MMR vaccine was not associated with an increased risk of autism even among high-risk children whose older siblings had autism. Despite strong evidence of its safety, some parents are still hesitant to accept MMR vaccination of

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their children due to the fake scientific report and news (DeStefano & Shimabukuro, 2019). To characterise and evaluate the dissemination of information to the community during a suspected TB outbreak, a model of effective information dissemination in a crisis was developed through a study of information dissemination during the incident (Duggan, 2004). In the food safety area, Lyu identified and compared the crisis communication strategies that organizations used to respond to a congenetic melamine-tainted milk crisis and public opinion in two Chinese societies (i.e., Mainland China and Taiwan) and found that Sanlu (a Mainland China-based organization) and KingCar (a Taiwan-based organization) demonstrated inverse pattern of the strategy adoption (Lyu, 2012). In the large-scale project area, Jeong used situational communication crisis communication theory and attribution theory to explain the public's responses to a corporation that caused an oil spill accident (Jeong, 2009). Sun investigated nuclear power in China from the perspectives of electricity preference and social perceptions and assessed the public Willingness-To-Pay (WTP) to prevent a local nuclear power plant. Research results indicate that the Chinese pay most attention to the development of nuclear energy when they are worried about nuclear accidents (Sun, Zhu & Meng, 2016). Following the anti-nuclear event in Jiangmen in Guangdong province, China, Li analyzed the causes and characteristics of nuclear public sentiment in depth and presented some relevant measures for preventing negative public sentiment in the era of new media (Li et al., 2015). Above all, most relevant studies include some significant ideas for our purposes. However, existing research methods are mainly qualitative rather than quantitative and post-mortem analysis rather than real-time decision-making.

Two bottlenecks, a lack of prior knowledge and the dynamic of public sentiment evolution, have caused this situation. On the one hand, the original events (large-scale projects, major incidents or scandals) which trigger the relevant public sentiments occur with low frequency, and the triggered public sentiments are diverse and non-duplicated. Thus, the key parameters (such as "posting rate of MicroBlog") of prior knowledge (such as decision models and data) for describing or predicting the scenarios of public sentiment systems are difficult to obtain in time. On the other hand, interdisciplinary and dynamic original events lead to the features of feedback, nonlinearity and instability of the relevant public sentiment systems. This also means that the key parameters of the decision models are adjusted over time. Therefore, it is more difficult for policy makers to build a quantitative evolutionary model and make an effective response decision based only on previous decision methods.

1.2. Insightful lessons from the perspectives of system dynamics (SD) and parallel control and management (PCM)

1.2.1. Lesson from the perspective of SD modelling

The SD research method focuses on system structure and simultaneously takes selectivity (decision-making processes based on information), self-discipline (multi-feedback processes) and non-linearity (time delay) into account (Rashwan, Abo-Hamad & Arisha, 2015; Torres, Kunc & O'Brien, 2017). It is a perspective and set of conceptual tools that helps us to learn about the structure and dynamics of complex systems. Additionally, the rigorous modeling method of SD enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations (John Sterman, 2000).

Several scholars have used SD models to study the diffusion mechanism of different complex systems, which are helpful for us to develop insightful lessons. The SD methodology is used to develop some increasingly complex models to investigate the process of innovation diffusion and enhance insight in the problem structure and increase understanding of the complexity and the dynam-

ics caused by the influencing elements (Maier, 1998). A diffusion model is employed to extend commonly used epidemic models in the study on analyzing dynamics of intra-organizational innovation implementation processes. The SD modelling and simulation results of this study provides structural explanations and offers insights into why, given various intra-organizational networks, management policies can make different results on whether and how innovations are adopted in an organization (Wunderlich, Größler, Zimmermann & Vennix, 2014). Furthermore, by applying system dynamics, Yu proposed a simulation model to study the public sentiment diffusion mechanism in dangerous chemical pollution water emergencies and discover effective response strategies (Yu Le-an, Ling & Wu Jia-qian, 2015). His research shows that the SD modelling methods are useful for describing, understanding and simulating the complex public sentiment diffusion systems and for making relevant optimization policies. More importantly, compared with decision-making theories based on large amounts of historical data, SD has the advantage of being able to predict the future based only on system structure. Therefore, when one lacks historical data, most complex social systems can be described and analysed using SD method (Morgan, Howick & Belton, 2017).

Public sentiment system is no exception. To solve the first bottleneck (lack of prior knowledge), the structure of the public sentiment system can also be represented by multi-feedback relationships, and its system functions can be achieved and controlled by SD method. Moreover, by now many mature statistical technologies, such as regression analysis, are available to help decision-makers obtain key parameters and build SD simulation models to respond to possible disasters and social crises.
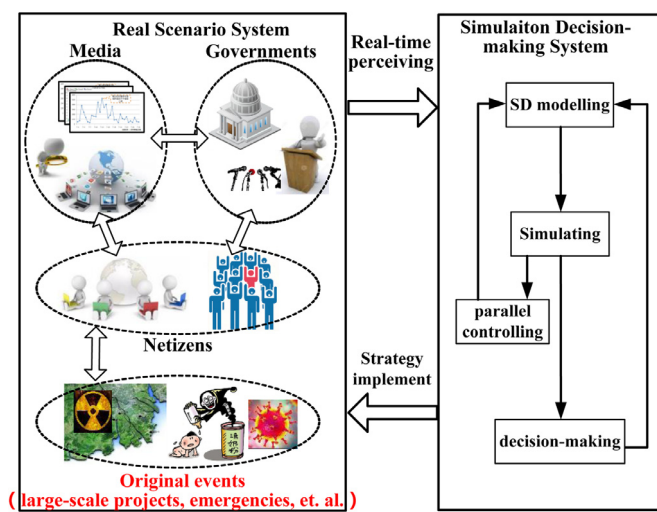
1.2.2. Lesson from the perspective of PCM theory

With the advent and development of Cloud Computing and the Internet of Things (IOT), the capacities of perception, computing, storage, transmitting and analysing have been greatly improved. In this era of new Information and Communication Technology (ICT), Artificial Society and PCM theory have been proposed by the Chinese Academy of Sciences and the National University of Defense Technology to provide an available decision-making paradigm to respond to the dynamically evolutionary scenarios of interdisciplinary disasters and social crises. This theory uses Multi-Agents modelling and simulation technology to build an artificial social system equivalent to the real system. By simulation computing in the artificial system, decision-makers are able to recognize the evolutionary mechanisms of disaster scenarios. Moreover, by comparatively analysing the artificial and the real systems, the simulation model of the artificial system is modified to parallel the actual situation in real time. Lastly, with the knowledge obtained from the simulation results, the evolutionary processes of disasters can be controlled and optimized by making the appropriate decisions in time (Wang, 2010).

Inspired by PCM theory, the public sentiment system, a type of crisis system, can be considered a real system carrying public attitudes and opinions. Thus, the second bottleneck (dynamic of public sentiment evolution) may be resolved based on both PCM theory and SD method. After building and running the artificial SD simulation system parallel with the public sentiment system, evolutionary scenarios can be predicted and effective response policies can be provided by decision-makers.

Therefore, a novel decision-making method "Parallel Evolution and Response Decision Framework for Public Sentiment (PERDFPS)" based on the theories of PCM and SD is proposed as a specific contribution of this paper. This method is structure-dependent rather than data-dependent and can be implemented in real-time, which makes it helpful to simulate, analyze and guide the evolution processes of dynamic public sentiment in the case of lack of historical knowledge on less-frequently occurring original events. The pa-

Table 1
Roadmap for implementing the PERDFNPS method.

Step		Description
3.1 Identify the decision problem		• Identify the type of the decision problem: the sentiment triggered by a periodic heated topic with enough investigable historical data or by an unconventional heated topic? • Selecting the relevant decision methods, data– dependent or structure– dependent?
3.2 Research hypotheses		• Reality hypotheses of the model: the simulation results of the model are consistent with the real scenarios. • Validity hypotheses of the response strategies: testable relationships between the response strategies and the controllable degree of public sentiments.
3.3 SD modelling		• Analysis of real scenario system from perspectives of structure. • Causal loop diagram modelling: abstracting the elements and the causal relationships between them from the scenario system; defining the circular causality loops of relevant modules of system. • Stock Flow diagram modelling: selecting levels, selecting rates and describing their determinants; selection of parameter values.
Simulating	3.4 Parallel controlling	• Reality testing: contrasting the simulation results to verify the reality hypotheses of the model. • Model improving: to achieve the rationality and consistency of the model.
	3.5 Decision analysis	• Response strategies setting. • Response strategies testing: simulation and discussion of strategy effects for verifying the proposed validity hypotheses.

Fig. 1. Parallel evolution and response decision framework for public sentiment.

per is organized as follows for achieving the contribution. Section 2 proposes the PERDFPS framework. And section "3 Methodology" is developed to abstract and present the PERDFPS methodology with a roadmap (Table 1) helping decision makers effectively use the novel method. Furthermore, the section "4 Empirical research" shows a whole case study to deduce the principle and verify the effectiveness of the PERDFPS method using the anti-nuclear mass incident in Jiangmen, China. Lastly, theoretical discussions, the limitations and future studies are presented in Section 5.

2. Parallel evolution and response decision framework for public sentiment based on system dynamics

PCM theory holds that social mass incidents are essentially unpredictable. However, one can now build artificial societies parallel to real-world societies and deduce their evolution in a computational experimental environment. In addition, with dynamic and real-time data, decision-makers are able to perceive coming disaster scenarios and response demand using artificial simulation models and create effective and timely coping strategies, policies and response solutions to control the real situations (Wang, 2010). Therefore, the "Parallel Evolution and Response Decision Framework for Public Sentiment (PERDFPS)" is proposed as a guideline for achieving this function. Moreover, within this framework (Fig. 1), according to the "scenario-response"-based emergency management paradigm (Bañuls, Turoff & Roxanne, 2013), the Public

Sentiment System (PSS) can be divided into two subsystems: the Real Scenario System (RSS) and the Simulation Decision-making System (SDS).

2.1. Real scenario system

As the source of real-time information, real scenarios are the basis for decision-making as well as the targets of public sentiment control. The original events, sentiment disseminators and sentiment regulators are the essential elements of the real scenario system. The original events (such as public health emergencies, food safety scandals and large-scale projects) may easily trigger relevant public sentiment. Public sentiment disseminators include the media, netizens, and others. The media triggers and influences the processes of public sentiment propagation through reporting and directing the news. In addition, netizens use social networks to express and communicate their own opinions, which results in the continued diffusion and evolution of public sentiments. Because the collective behaviours of the netizens comprehensively reflect their attitudes towards source events, their support or opposition are essential factors for the government in making an efficient response decision. Generally, the government response departments dealing with the emergencies or large-scale projects assume the greatest responsibilities as public sentiment regulators. By taking measures such as holding lectures and seminars, press conferences on the events, and by releasing positive news, they supervise, guide and even control the development of the public sentiments.

2.2. Simulation decision-making system (SDS)

Based on PCM theory, the simulation decision-making system is a closed-loop functional circuit consisting of four steps: SD modeling, simulating, decision-making and parallel controlling. In the first step, using real-time perception (which includes the processes of information collecting, analysing and abstracting), the characteristic elements of the public sentiment system, including source events, sentiment disseminators and sentiment regulators, can be extracted from real scenarios. Based on the SD method, the Causal Loop Diagram model is suitable for describing the relationships between the elements of public sentiment systems. In addition, after setting the parameters and calculating rules, the Stock Flow Diagram model, which is based on the qualitative Causal Loop Diagram model, can be built to describe the dynamic system structure and simulate its functional mechanism quantitatively. In the second step, simulation results of public sentiment diffusion and evolution at a future time can be obtained by importing real-time status data perceived from real scenarios into the Stock Flow Diagram

model and running it. Next, to keep simulation models consistently parallel with real scenarios, decision-makers should dynamically adjust the parameters and structures of the Stock Flow Diagram models by observing and analysing the running effect of models and the real-time status of the scenarios. In this way, the validity and reliability of the simulation results of the SD Stock Flow Diagram model can be gradually improved. In the last step, given a reliable SD model, different response strategies or policies can be tested, verified and optimized in the simulated environment.

3. Methodology

Roadmap is useful for decision makers to know when and how to use a modelling and simulation method for dealing with practical problems (Davis, Eisenhardt & Bingham, 2007). For implementing the PERDFNPS method, we develop a roadmap that describes the principles and steps shown in Table 1 (Thompson, Howick & Belton, 2016). No matter how the PERDFNPS method is carried out, the steps do not occur in neat sequence. Specifically, the steps of SD modelling and parallel controlling constitute an iterative process for cultivating a rational decision model.

3.1. Identify the decision problem

As a structure-dependent decision-making method, the PERDFNPS framework is applicable for response to the public sentiments without enough historical data. Therefore, in the implementation stage, the decision makers must firstly determine what type of decision problem it is: Is there enough historical data for building a model for this event? Or is the PERDFNPS method suitable for the decision problem? If public sentiment is triggered by a periodic heated topic with enough investigable historical data, the decision-making model can be constructed based on the data-dependent statistical methods. For example, the training data used for cultivating the model of its public sentiment system for the presidential election every four years, can be obtained from the social network services including Twitter, Facebook (Wang, Can, Kazemzadeh, Bar & Narayanan, 2012). Conversely, if the public sentiment is triggered by an unconventional or non-periodic heated topic such as a nuclear-related event without sufficient investigable historical data, the SD simulation model can be cultivated to describe and solve these kinds of problems based on the structure-dependent PERDFNPS methods.

3.2. Research hypotheses

Two kinds of hypotheses are proposed for the PERDFNPS method according to the requirements of simulation reality and decision validity.

(1) Dynamic simulation reality hypotheses:

Hypothesis 1, the simulation results of the cultivated SD model are rational and consistent with the real scenarios.

The rationality of the cultivated SD model and the consistency between its simulation results and the real evolution trends of the public sentiment are essential to achieve scenario rehearsal and response effectively in the decision-making processes (Thompson et al., 2016). Thus, we firstly present hypothesis 1. Then, we begin to cultivate our SD model and verify the hypothesis for a specific case through comparison between the real scenarios and the simulation results (Section 4.3). Of course, the rational initial general SD model is very important because it determines the efficiency for reality improvement of the descendant models.

The best method for verifying the dynamic reality of a simulation model is testing the consistency between its simulation results

and the real evolution trends in a real-time case. However, it is difficult to achieve this process in our empirical research. Therefore, the special Hypothesis 2 for the subsequent section of empirical research is proposed.

Hypothesis 2, information of the past scenario of the public sentiment, is unknown but can be gradually revealed through evolutionary process.

The goals of the empirical research are to verify whether a reliable simulation model that parallels the real public sentiment scenario can be developed and whether the response strategies based on the validity hypotheses can be optimized. For comparing the simulation results with the real-time scenarios, we assume that the data of the scenario is unknown but will be gradually revealed through evolutionary process in the experiment. The public sentiment event is considered a real-time scenario to verify the rationality and consistency of the parallel simulation models to be cultivated.

Hypothesis 1 and 2 can be validated by reality testing (Section 3.4).

(2) Decision validity hypotheses

The public sentiment system is a complex social network system. The various decision response behaviours of government drive the evolutions and diffusions of public sentiments and ultimately decide the results of the original events through affecting the attitudes of people. Therefore, four testable decision validity hypotheses are proposed to explore the effective response strategies for guiding the evolution of the public sentiment with the PERDFPS method.

Firstly, the government's response measures, including social stability risk assessment, answering questions from the public, giving lectures on the original event-related knowledge and so on, is significant for guiding the evolution processes of the public sentiment events. Higher degree of government response results in a more controllable public attitude to the public sentiment event (Zhang, Qi, Ma & Fang, 2010). The amount of times the government responds to an event can reflect the degree of government response. Therefore, the relevant Hypothesis 3 is proposed as follows.

Hypothesis 3 is that, firstly, the more times the government responds, the more controllable the public attitude to the public sentiment event is.

Secondly, response time represents the time-delay in the government response processes. Another important factor is controlling the evolution processes of the public sentiment events. A timely response means higher response speed which leads to a lower heat rate and a higher controllable degree of public sentiment (Le-an et al., 2015). Similarly, Hypothesis 4 is proposed as follows.

Hypothesis 4 is that a higher response speed (or short response time) of government leads to a higher controllable degree of public sentiment.

Furthermore, the degree of information transparency and the degree of popularity of original event-related knowledge also make significant influences to the evolution trends of the public sentiment event. The degree of information transparency represents the disclosure degree of the original event-related information, and the degree of popularity of original event-related knowledge reflects how the knowledge related to safety and risk was popularized locally. Scholars analyzed the response processes of public sentiment events and believed that these two factors are positively related to the controllable degree of large scale project-related public sentiment (Li et al., 2015). Hypotheses 5 and 6 are proposed as follows.

Hypothesis 5 details that a higher degree of information transparency leads to a higher controllable degree of public sentiment.

Hypothesis 6 is that a higher degree of popularity of original event-related knowledge leads to a higher controllable degree of public sentiment.

3.3. SD modelling

(1) Analysis of real scenario system from perspectives of structure.

The SD approach emphasizes how causal relationships among system structures can influence the functions, behaviours and evolution processes of a system. Analysis of the boundary and structure of a public sentiment system is the first step to building its SD model. System boundaries include the basic elements of the system. The function modules of the system consist of the elements that have direct causal relationships with each other.

The public sentiment system can be divided into original events and three interactional modules according to the different roles of the sentiment disseminators (Le-an et al., 2015): the media module, the government module, and the netizen module. Firstly, the media module: Once a food safety scandal, public health incident or large-scale project does happen, it is easily noticed and reported by (Internet) media. Media plays a major role in guiding public opinion and can influence the evolutionary processes of public sentiments by affecting the attitudes of netizens regarding the original events. At the same time, the media's behaviours are monitored by the government and influenced by the opinions or sentiments of netizens. Secondly, the government module: Most public health policies and large-scale projects are proposed or supported by governments. Then, once a large-scale project begins or a public health incident occurs, the relevant government departments should take effective emergency response measures (such as open information, popular science propaganda, releasing the official news, setting laws and regulations, and holding a press conference) to guide the development of original events and control the diffusion of triggered public sentiments in a timely manner. Furthermore, the netizen module: Original events may affect social and economic benefits, damage the ecological environment and even directly threaten our life safety. Therefore, they quickly garner attention from people and trigger various public opinions or sentiments. There are both advantages and disadvantages for various people, and thus netizens are divided into three groups: opponents, supporters and neutrals. These groups express their own opinions and sentiments online and this kind of behaviour turns original events into controversial issues. In addition, the main attitudes of netizens influence and even decide the response behaviours of the relevant media and government departments, as they reflect public opinion.

(2) Causal loop diagram modelling

The SD approach describes a system as a series of simple processes with positive and negative circular causality loops (Forrester & Senge, 1980; Sterman, 2000). The feedback function of a positive loop is self-reinforcing and amplifying; the feedback function of a negative loop is dampening. The public sentiment systems evolve continually under the influence of the interactions between the feedbacks. Based on the structure and mechanism of real scenario public sentiment system of a concrete case, the qualitative causal relationships and the circular causality loops of relevant modules can be defined. The concrete examples of this process are shown in Section 4.2.1.

(3) Stock and flow diagram modelling

Causal loop diagrams aid in visualizing a system's structure and behavior, and analyzing the system qualitatively. To perform a more detailed quantitative analysis, a causal loop diagram is transformed into a stock and flow diagram. A stock and flow model helps in studying and analyzing the system in a quantitative way; such models are usually built and simulated using computer software such as VenSim (Martinez-Moyano, 2012; Rahmandada & Sterman, 2012).

A stock is the term for any entity that accumulates or depletes over time. A flow is the rate of change in a stock. The key step to build the stock and flow diagram is converting the system description into level and rate equations (Torres et al., 2017). Usually, the parameters and initial conditions of the equations can be estimated using statistical methods, expert opinion, market research data or other relevant sources of information (Sterman, 2001). In a decision-making process for a non-duplicated public sentiment triggered by a major public health incident or a large-scale project, because the decision makers lack prior data and knowledge, the parameters of the initial equations of the 1-general SD model can be referenced from the developed models of historical cases which are similar with the current event in type, system structure and situation. By analyzing and refitting the real-time data gradually collected from the real scenarios, the parameters are modified and the equations are improved.

To achieve the target of public sentiment simulation and control, the variables of the stock and flow model are classified into two categories, including state and control variables. The latter is classified into two subcategories, including parallel cultivating control and decision-making control variables. Each kind of variable has relevant functions in the model. According to the literature (Rahmandada & Sterman, 2012), the variables of the constructed SD model should meet the minimum and preferred reporting requirements for research reproducibility, communication and transparency. Appendix A shows an example of a constructed and defined SD model of all variables and their equations.

3.4. Simulating and parallel controlling

Non-duplicated source events trigger diverse public sentiments and lead to a lack of prior knowledge (the parameters to describe or calculate the key variables) in order to make an effective response decision. In addition, even if we obtain some experience from the public sentiment triggered by a similar original event, due to their various spaces, locations and social environments, the evolution processes of the public sentiments are too different to build a simulation and decision model in one step using the most traditional methods. Thus, in this paper, we use PCM theory to cultivate the SD simulation models dynamically and to keep the models parallel with real public sentiment systems in order to obtain accurate simulation results and reliable response solutions (F. Wang, 2010). The parallel controlling principles are shown in Fig. 2.

(1) 1-generation SD Model constructing. The parallel simulation decision-making system enters into the emergence response state immediately after "Scenario 0″ of a new original event occurs. At this point, decision-makers should decide whether this event has ever occurred using a semantic searching and matching in an existing model library (Wu et al., 2017). If there is a public sentiment scenario very similar to the current scenario through the perspectives of event type and system structure, the relevant simulation model of the scenario is chosen as the initial model "1-generation SD Model", However, there are usually no extremely similar scenarios for a non-duplicated public sentiment event. In that situation, the parameters of the initial equations of the 1-generation SD model can refer to the developed models of historical cases which are similar with the current event in type, system structure and situation. Regarding the historical cases, it is very difficult to find the most similar one in an emergency situation. We can still improve and cultivate our models iteratively by adjusting them in parallel with
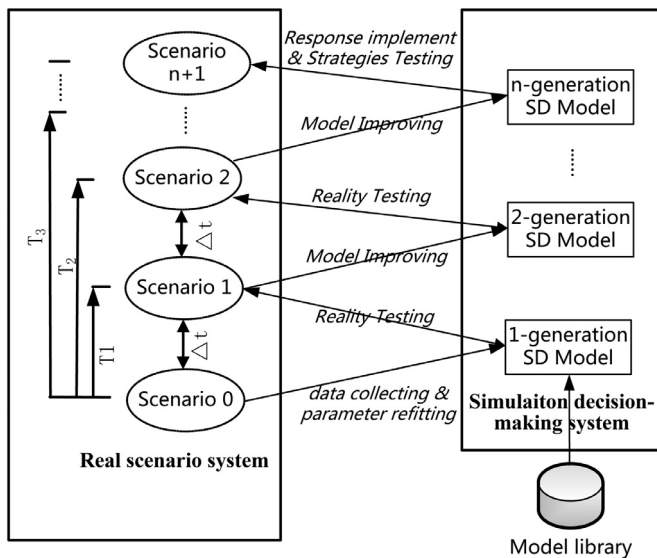
Fig. 2. The principles of parallel controlling.

the real-time scenarios even if the selected historical case is not identical to the current public sentiment event. Of course, the more similar a selected historical case is, the less iteration there will be, so the improved decision-making model will be obtained quickly.

(2) Reality testing. We can validate hypothesis 1 and 2 by rationality and consistency testing. The rationality and consistency between the models and real public sentiment systems should be discussed by comparing the values of the key system state variables of the simulation results with the real scenarios or concrete cases. The cultivated simulation models are considered consistent with the real scenarios and can be used to make an effective response decision if the evolutionary trends and peak values of the key state variables of simulation results, such as "Increments of support posts" and "Increments of opposite posts", are similar with the real-time data from scenarios during the same time span. It also means these hypotheses are tenable. Otherwise, if a simulation result of the SD model is different from the real scenario, the simulation model should be improved by persistent parameter adjusting and contrasting. We can test model reality by calculating the Goodness-of-fits (GOF) between the real time series and the simulated time series of the key state variables (Wooldridge, 2006).

(3) Model improving. By analyzing and refitting real-time data gradually collected from real scenarios, the parameters are modified and the equations are improved. In the entire parallel controlling process, the real time information from the various stages of the real scenarios (from Scenario 0 to Scenario n) should be collected, integrated, and analyzed at a specific time-interval, "$\triangle t$". At the same time, modifying processes such as parameter refitting and data updating can be used to continually improve the simulation models from "1-generation SD Model" to "n-generation SD Model", ensuring that simulation results are consistent with the real scenario in the parallel evolution processes. Regarding the parameter fitting into the model cultivating process, we constructed the 1-generation SD model and the other n-generation SD models in different ways. Take the case shown in the empirical part of this paper as an example. On the one hand, most of the equations of the 1-generation SD model based on the literatures ((Li et al., 2015), Tian, 2011), (Zhang, 2012) and (Le-an et al., 2015) are obtained using parameter fitting with the data of 36 similar cases such as the "Sanlu milk powder incident" from "people.com", On the other

hand, for the n-general models, we do not have to fit the parameters to improve the equations. Only real-time data needs to be collected to draw the curves of the key state variables such as "Increment of posts" and "Increment of news" during the time-interval ($\triangle t = 24$ h). After contrasting the simulation results of the n-generation model and the scenario n, the parameters of the equations are adjusted and the model is improved to approach the real scenario in an iterative and parallel way. When an n-general model and its simulation results are consistent with the real scenarios, it means that the model has passed reality testing and has become a cultivated model.

(4) Response strategy improving. By analyzing the simulation results after running a cultivated n-general SD model, the evolution processes of the public sentiment of "Scenario $n + 1$" and the effects of the response measures in a future time can be predicted and shown. Based on these simulation results, decision-makers are able to improve their response strategies and solutions in time. To achieve the improvement process, the variables of the SD model are classified into two categories, including state and control variables. Most of the variables are uncontrollable state variables from the perspective of government, such as *Increment of posts* and *news Increment*. This kind of variable is used to show the current state and evolutionary trend of the public sentiment system. The other variables, such as "times of government response" and "response time of government," are controllable. The control variables can be tentatively set by the decision makers to represent different response strategies. The effects of different strategies can then be tested by reviewing the simulation results with the cultivated n-general SD model. The optimal strategy can be obtained by adjusting the control variables. As shown in the stock and flow diagram model (Fig. 6), the interactions between these system variables drive the evolutions and diffusions of public sentiments and decide the final results of the original events, as seen through the attitudes of people.

In the end, when the entire emergency response process ends, the latest parameters and structure of the simulation model are recorded and archived in the model library for the next similar public sentiment.

3.5. Simulating and decision analysis

Some advanced SD software tools, such as Vensim, Stella and Anylogic, are available to help decision-makers construct, run and analyse the SD simulation models of the public sentiment systems and to create the optimized response policies and solutions in a graphic and visual way (Rahmandada & Sterman, 2012). According to the evolutionary cycle and system boundary of the specific public sentiment system, and after setting the main calculating parameters such as simulation step size and run time, the simulation process can be implemented. To propose suitable response solutions, the relevant decision analysing process should include two aspects:

(1) Response strategies setting. The control variables can be tentatively set by the decision makers to represent different response strategies. However, most of the variables, especially state variables, are uncontrollable from the perspective of government. Next, taking the public sentiment of anti-nuclear mass incident as an example (Section 4) and according to the "Validity hypotheses of the response strategies" based on relevant literature (Le-an et al., 2015; Li et al., 2015; Zhang et al., 2010), we can choose four controllable variables, "Times of government response", "Response time of government", "Degree of information transparency", and "Degree of popularity of nuclear knowledge", to explore the effective response strategies
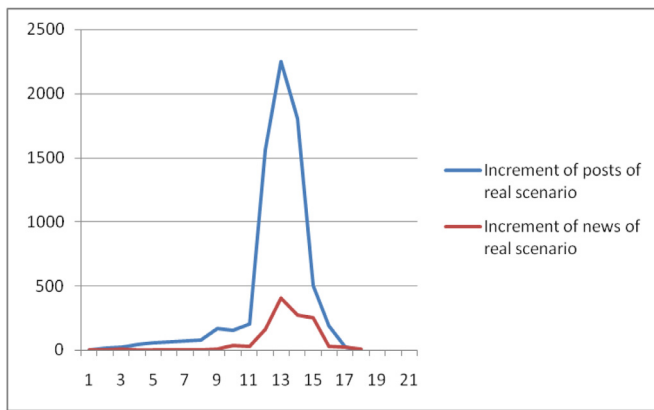
Fig. 3. Increments of media and comments per day in the Jiangmen anti-nuclear mass incident.

Table 2
Main response measures of government in the Jiangmen anti-nuclear mass incident.

Date	Response measures
4th	The Jiangmen government released the report of the social stability risk assessment of the nuclear project.
5th	The deputy general manager answered questions from the public.
8th	Three lectures on nuclear knowledge are given by the Jiangmen government.
9th	Professor Zhou participates in the propaganda lectures on nuclear knowledge, telling the public that the project is safe.
12th	Announcement of the determination of the nuclear project is delayed for ten days.
13th	The nuclear project is terminated by the government.

for guiding the evolution of the public sentiment. The series of different response strategies are shown in Table 4. The R0 strategy is the baseline strategy extracted from this real case; the other response strategies, including A1~A4, B1~B4, C1~C4, D1~D4 and E, are set with different specific values of the key control variables, respectively.

(2) Response strategies testing. The effects of different strategies can then be tested by reviewing the simulation results with the cultivated n-general SD model. Policy-makers would be able to control the system state variables and create an effective and optimized response strategy to guide the public sentiments by adjusting or resetting the values of the four key controllable variables in the SD simulation models. Some practical measures, such as enhancing the credibility and degree of information transparency of government, are available to improve the control performances of public sentiments. However, increasing these variable values always brings higher response times or costs. Thus, balanced considerations should be included in the decision-making processes.

4. Empirical research

4.1. Case analysis (including "Indentify the decision problem" and "Research hypotheses")

In this section, the anti-nuclear mass incident sparked by a nuclear fuel processing base project near Jiangmen city in Guangdong province is taken as a case study to verify the feasibility and validity of the PERDFPS method proposed in Section 3 above. The announcement of the result of the social stability risk assessment of the nuclear project is considered the source event of the media module of this public sentiment system. In addition, by choosing and analyzing the increment data of Baidu news and Xinlang Blog posts (Fig. 3) during July 5–19, 2013, and the relevant government response measures (Table 2), the key parameters of the initial stock flow diagram model and the initial data of the simulation process of public sentiment evolution can be extracted gradually. Due to the actual evolution cycle of public sentiment lasting only 15 days, it is too short to prepare enough data and develop a reasonable simulation trend. The simulation model is thus set for running 12 h per day. Therefore, the simulation cycle is translated or expanded from 15 days to 240 h. The main data used in this paper is collected from references and websites (CNSA, 2015; Li et al., 2015). Moreover, some variables or parameters of the model should be adjusted according to the demand of the actual simulation experiment. For example, some unstructured behaviour data, such as government response behaviours, should be ranked into the quali-
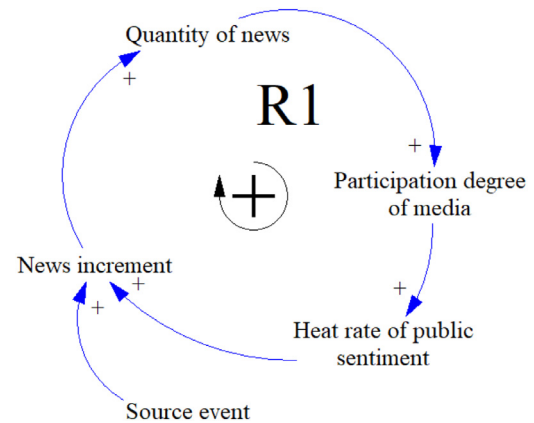

Fig. 4. The causal loop diagram of media module.

fied and controllable variables *Quantity of government response* or *Increment of government response*. Note that the data shown in Fig. 8 are considered unknown information at the beginning of the simulation experiment and will be revealed gradually during the simulation processes. In fact, this primary data is used to verify the reality and validity of our parallel simulation model by describing the real scenarios and comparing them with the artificial ones. Therefore, the decision problem of this case is structure-dependent and can be described and solved with the PERDFNPS method based on the 6 hypotheses proposed in Section 3.

4.2. 1-gennral SD modelling

4.2.1. Causal loop diagram model

Plans by the China National Nuclear Corporation (CNNC) to build a nuclear fuel-processing base near Jiangmen city in Guangdong province, China, in 2013, sparked an anti-nuclear mass incident and relevant public sentiment in that city. Taking this anti-nuclear mass incident as a concrete case, we can analyze the boundary, structure and evolution mechanism of the public sentiment system of this event and build a relevant qualitative causal loop diagram model. This model is divided into three main modules: the media module, the netizen module and the government module.

(1) The causal loop diagram of the media module is a positive feedback loop R1 (Fig. 4). Once the nuclear event does occur, the relevant news is released on an ongoing basis. In addition, as the event evolves, the quantity of news and the participation degree of media both increase. At the same time, due to media influence, the increased participation degree of media always leads to a higher rate of public sentiment and results in more news increments.

(2) The causal loop diagram of the netizen module is comprised of five positive feedback loops from R2 to R7 (Fig. 5). The loops
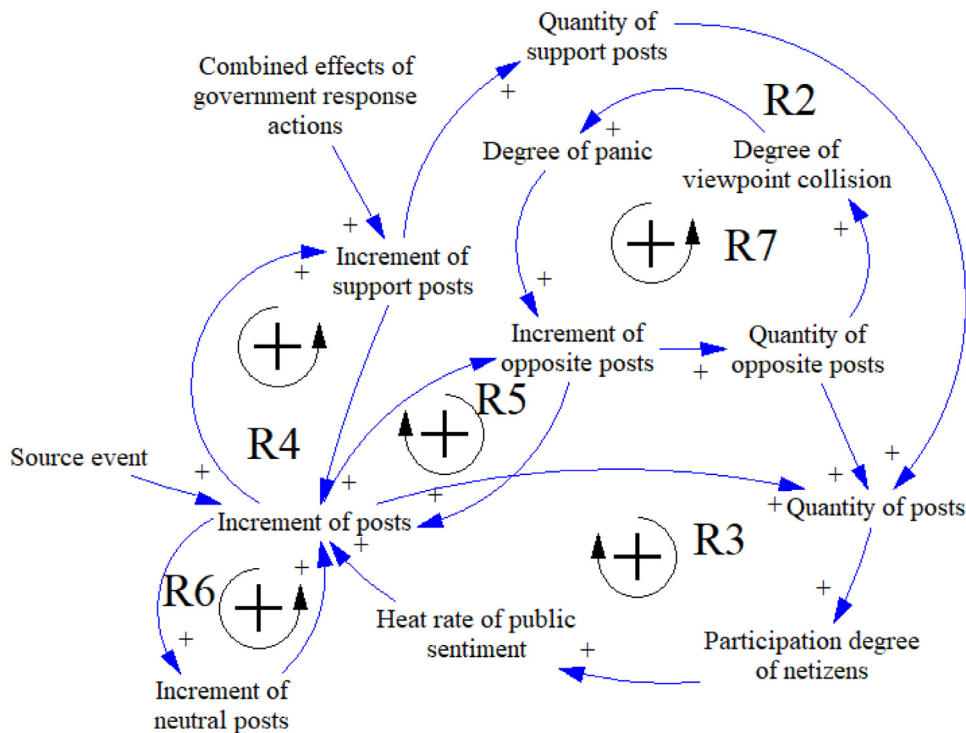
Fig. 5. The causal loop diagram of netizen module.

illustrate that, after the source event happens, the quantity of posts increases because of netizens' large-scale micro-blog posting behaviours. The increment of posts, which includes the increment of support of posts from project supporters, the increment of opposite posts from project opponents and the increment of neutral posts from neutral netizens, gradually contribute to the total quantity of the posts. In addition, under the influence of the combined effects of government response actions, the quantity of support posts increases with the accumulation of the increment of support posts, resulting in the accumulation of the total quantity of posts. Similarly, under the negative effects of social panic caused by potential nuclear safety problems, the quantity of opposite posts increases with the accumulation of the increment of opposite posts; as a result, the total quantity of posts increases. The accumulation process of the neutral posts is similar to the processes of the support and opposite posts. The increase in total quantity of posts also means an increase in the participation degree of netizens and the promotion of the heat rate of public sentiment, which also might lead to a further increase in the increment of posts.

(3) As shown in Fig. 6, the causal loop diagrams of the government module consist of one negative feedback loop B1 and one positive feedback loop R8. Once a nuclear event does occur, the government enhances their supervision and takes other effective measures, such as open information and popular science propaganda, to guide and control the situation. With this increase in government measures, the combined effects of government response increase, which leads to an increase in the increment of support posts, and a decline in the heat rate of public sentiment. With the combined effects of this negative feedback loop of the government module, the diffusion and evolution of nuclear public sentiments can be effectively guided and controlled.

In the above causal loop diagrams, the government's emergency response measures are synthetically considered into the increment of government response. In addition, the variables in degree of government response, credibility of government and degree of popularity of nuclear knowledge also lead to weighted impacts on the combined effects of government response actions. Under normal circumstances, an obvious positive relationship exists among the three variables. The degree of government response comprises quantitative response actions, including supervision and intervention. Government credibility means public appeal and influence and reflects the people's trust in and satisfaction with their government's response. Thus, government credibility is affected by the degree of information transparency and the degree of response satisfaction in the causal loop diagrams. The degree of popularity of nuclear knowledge is used to describe the extent of people's basic knowledge regarding a nuclear accident, nuclear radiation and nuclear safety. Usually, government response actions are acceptable and have a positive effect if most local people have sufficient nuclear knowledge. Moreover, the degree of response satisfaction indicates the extent to which the result of the response actions is acceptable and satisfactory to local people.

4.2.2. Stock and flow diagram model

The evolution processes of the nuclear public sentiment system are driven by a multi-feedback mechanism, which leads to some delays in the propagation and response processes. Thus, the nuclear public sentiment system should be described as a number of nonlinear and multi-feedback relationships, such as the exponential dependence relationship between interactive system variables such as *Increment of government response*, *Increment of posts* and *News increment*. Taking the incident of "anti-nuclear public sentiment in Jiangmen city, Guangdong province" as an example, and according to the main causal loops in Section 3.1, the SD stock flow diagram model of the nuclear public sentiment system is shown in Fig. 7.

(1) Stock Flow Diagram model of the media module.

Because the source event doesn't last long, the variable *Increase rate of news* can be defined as a LOOKUP or fitted function and described directly according to the captured short-term history data. The variable *Quantity of news* is influenced by the variable *Heat*
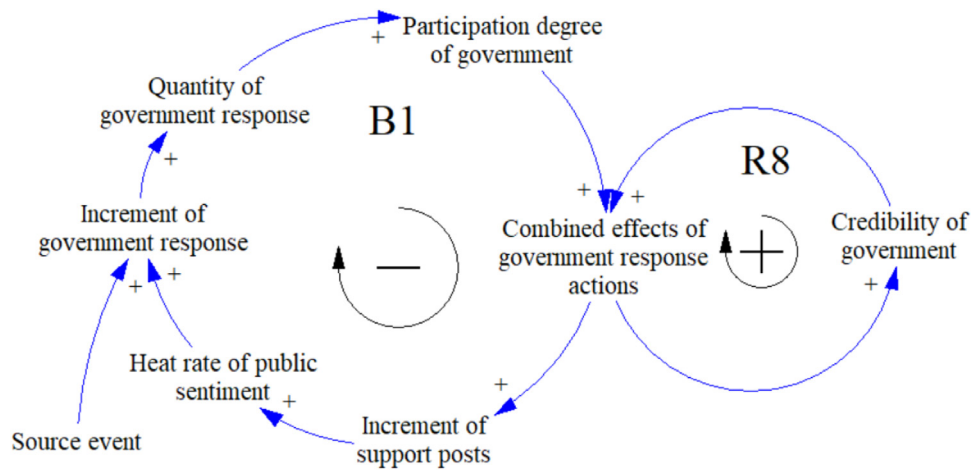
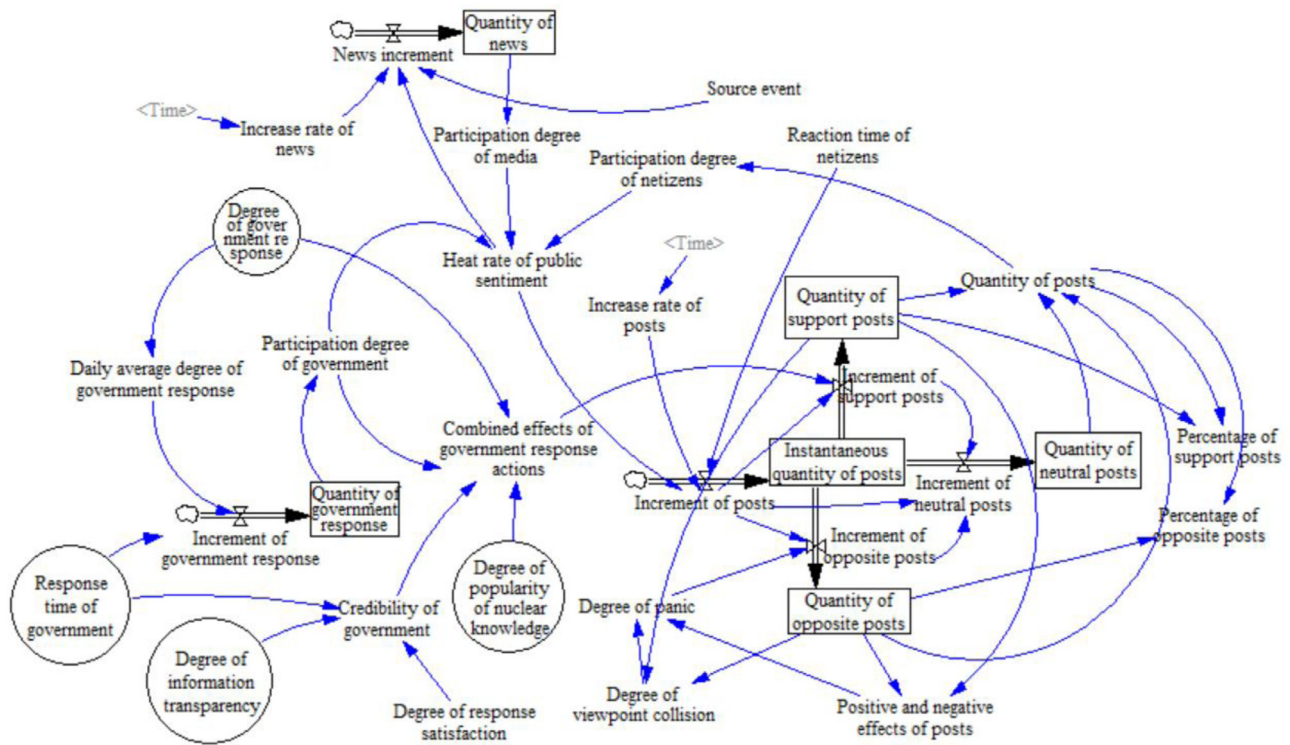Fig. 6. The causal loop diagram of government module.

Fig. 7. The SD stock and flow diagram model of the nuclear public sentiment system.

rate of public sentiment, which is constrained by the variables *Participation degree of government*, *Participation degree of media* and *Participation degree of netizens*. Referring to the evolution mechanism of public sentiment (Le-an et al., 2015; Zhang, 2012), the functional relationships of the variables can be defined respectively as the formulas (1–4). In these formulas, we assume that there is no delay in the transmission processes of Baidu news, and the variable type of source event is Boolean (its value equals 1 if the source event is trigged).

(2) Stock Flow diagram model of the netizen module.

The posting reaction of the netizens after receiving news information causes a time-delay effect and the variable *Increment of posts* is also influenced by the variable *Heat rate of public sentiment*. The variable *Increase rate of posts* can be defined as a LOOKUP or fitted function and described directly according to the captured short-term history data. The function of Increment of posts is then

constructed as a formula (5). Referring to the evolution mechanism of public sentiment (Le-an et al., 2015; Zhang, 2012), the functional relationship between the variable *Participation degree of netizens* and the variable *Quantity of posts* is shown in formula (6). The variables *Increment of support posts*, *Increment of opposite posts* and *Increment of neutral posts* are subject to the constrained variables *Degree of panic* and *Combined effects of government response actions*. In addition, the variable *Degree of panic* is decided by the variables *Degree of viewpoint collision* together with *Positive and negative effects of posts*. The functions describing the above variables and evolution rules are set as formulas (7–12). Additionally, as the accumulations of the above variables, the variables *Quantity of support posts*, *Quantity of opposite posts*, *Quantity of neutral posts* and *Quantity of posts* are defined as formulas (13–17).

(3) Stock Flow diagram model of the government module.

According to the articles and reports about this anti-nuclear mass incident (CNSA, 2015; Li et al., 2015), the government response measures, such as open information, popular science propaganda, releasing the official news, establishing laws and regulations and holding a press conference, can be considered as the decision-making control variable "Times of government response". The variable *Increment of government response* is decided by the variable *Average degree of government response* (formula 20). At the same time, due to the influence of delays in response time, it is subject to the variable *Response time of government*, so that the representation of the variable *Increment of government response* is defined as formula (18). As the accumulation of the *Increment of government response*, the variable *Quantity of government response*, which reflects the government's participation degree in this incident, is defined as formula (19). In addition, referring to the similar evolution mechanism of public sentiment (Le-an et al., 2015; Zhang, 2012), the variable *Combined effects of government response actions* is decided by the combined variables *Degree of popularity of nuclear knowledge* and *Credibility of government*. Moreover, the variable *Credibility of government*, which is subject to the variables *Response time of government*, *Degree of information transparency*, *Degree of panic* and *Times of government response*, is described as formula (21).

The variables of the SD model are classified into two categories: state, parallel cultivating control and decision-making control variables. Each type of variable has relevant functions in the model. To meet the minimum and preferred reporting requirements for research reproducibility, communication, and transparency (Rahmandada & Sterman, 2012), Appendix A is developed to clearly explain all the variables defined in this research.

4.3. SD model cultivating and parallel controlling with reality testing

(1) 1-generation model constructing

The Stock and Flow Diagram of the 1-generation SD Model is constructed in Section 4.2 according to the initial scenario (Fig. 7). The model cultivation and parallel control processes including 7 iterations are shown in Fig. 8. At the beginning of the simulation, we lack sufficient data to fit certain parameters of the 1-generation model. The variables "Increase rate of posts" and "Increase rate of news" are defined temporarily as formulas (22) and (29) (in the appendix) by collecting and polynomial fitting the 240 h of data (from July 15th to August 3rd) of the similar public sentiment triggered by the Changsheng Vaccine event from ef.zhiweidata.com (Fig. 8-①), because these two events have the similar "happening, developing, declining, and extinction" life cycle.

(2) 1-generation model testing and improving.

In the parallel iteration processes, the time-interval for improving the models is set as "$\triangle t = 24$ h", We constructed the improved n-generation formulas based on the "Minimum Sum of Squared Errors" algorithm with the real data during $n\triangle t$, and we tested the reality of the model based on "Goodness-of-fit formula" with the real data during $(n+1)\triangle t$. Considering the scenario during the 48th hour as Scenario 1 (Testing period of 1-generation model $T_{Testing-1} = 2\triangle t$), assume that the real scenario evolves under the combined influences of the media, netizens, and government. After importing the initial data of the first hour of this case and simulating it for 48 steps (hours), the evolutionary trends of the variables "Increment of posts" and "Increment of news" can be drawn into Fig. 8-②. The simulated time series (orange curves) are both obviously too steep to match the real situations (blue curves). The model reality is tested by calculating the Goodness-of-fits ($GOF = 1 - \frac{\sum (y - y*)^2}{\sum (y - \bar{y})^2}$, $GOF \in (-\infty, 1]$) between the real time series and the simulated time series of the key state variables. In this formula,

y is the observed posts/news increment value, $y*$ is the simulated value (Wooldridge, 2006). We use "GOF_{dp}" and "GOF_{dn}" to indicate the GOF of the "Increment of posts" and "Increment of news" by the day respectively. After programming and calculating, GOF_{dp} and GOF_{dn} are -1276.29 and $-24,726.47$, respectively. Therefore, the simulation results show that the "1-generation Model" is very different from Scenario 1 during $T_{Testing-1}$.

To ensure that the simulation results are consistent with real scenarios, we developed a "Minimum Sum of Squared Errors" algorithm to improve the models. With this algorithm, each polynomial coefficient of $(n-1)$-generation "Increase rate of posts" and "Increase rate of news" formulas is traversed within a certain range, and the sum of squared errors between the observed real value series and the simulated value series is calculated for different coefficient combinations through multiple iterations. Then, the optimal coefficient combination with the minimum sum of squared errors is selected to be the polynomial coefficients of the "Increase rate of posts" and "Increase rate of news" formulas of the n-generation model. After inputting the 48 h of Scenario-1 data, the 2-generation variables "Increase rate of posts" and "Increase rate of news" are defined as formulas (23) and (30) in the appendix (also shown in Fig. 8-②).

(3) 2-generation model testing and improving.

Considering the testing period of the 2-generation model as $T_{Testing-2} = 72$ h ($3\triangle t$), the real scenario continues to evolve from Scenario 1 to Scenario 2 for 24 h($\triangle t$). After simulating for 72 h, the calculated GOF values and drawn evolutionary trend curves (Fig. 8-③) of the variables "Increment of posts" and "Increment of news" both show that the 2-generation model is much better than 1-generation model. However, GOF_{dp} and GOF_{dn} are still as low as -1.13 and -219.34, respectively, which means the 2-generation model cannot simulate the real Scenario 2 during $T_{Testing-2}$ or help us to predict the evolutionary trend of the public sentiment. Therefore, after calculating the "Minimum Sum of Squared Errors" between the observed 72 h of Scenario-1 data and the simulated value series, the optimal coefficient combination is selected as the polynomial coefficients of "Increase rate of posts" and "Increase rate of news" formulas of the 3-generation model shown in Fig. 8-③.

(4) From 3-generation to 7-generation model.

Similarly, models are tested and improved from 3-generation to 7-generation after a set number of parallel iterations. The variables "Increase rate of posts" are defined as formulas from (24) to (28) and the variables "Increase rate of news" are defined from (31) to (35) in the appendix. The simulated trend curves are becoming more and more similar to the real curves, and the GOF_{dp} and GOF_{dn} of the models are increasing in the iteration processes (Fig. 8-④∼⑧). Finally, the cultivated 7-generation model is obtained with high GOF values ($GOF_{dp}=0.87$ and $GOF_{dn}=0.89$). Although the simulated curves are still smoother than the real scenarios, the overall public sentiment trend is consistent with the real scenarios (Fig. 8-⑧).

Regarding public attitude, when the simulation runs to the 120th hour (the 10th day), the percentage of support posts drops to 6% and the percentage of the opposite posts rises to 38%. The curves shown in Fig. 9 are consistent with the real nuclear project case that was eventually cancelled. Therefore, the cultivated 7-generation model can simulate and match the evolutionary real scenarios very well. Meanwhile, the simulation results also indicate that the dynamic reality hypotheses proposed in Section 3.2 are tenable.
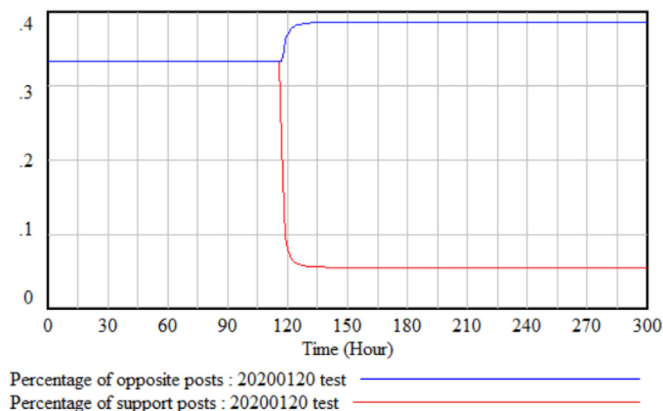
Fig. 8. Parallel iteration processes of the n-generation models.
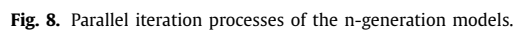
Table 3
Control variables of response strategies setting and simulated public attitudes.

Strategies	Key control variables of response strategies				Simulated public attitudes	
	Times of government response	Response time of government	Degree of information transparency	Degree of popularity of nuclear knowledge	Percentage of support posts	Percentage of opposite posts (%)
R0	7	2	0.5	50	5.56%	38.69
A1	1	2	0.5	50	4.03%	38.92
A2	4	2	0.5	50	4.76%	38.8
A3	14	2	0.5	50	7.4%	38.44
A4	70	2	0.5	50	21.4%	36.84
B1	7	0.5	0.5	50	5.6%	38.67
B2	7	1	0.5	50	5.58%	38.67
B3	7	4	0.5	50	5.51%	38.68
B4	7	6	0.5	50	5.46%	38.69
C1	7	2	0.1	50	5.54%	38.68
C2	7	2	0.3	50	5.55%	38.68
C3	7	2	0.7	50	5.57%	38.67
C4	7	2	0.9	50	5.57%	38.67
D1	7	2	0.5	10	2.63%	39.2
D2	7	2	0.5	25	3.73%	38.98
D3	7	2	0.5	100	9.22%	38.26
D4	7	2	0.5	250	20.2%	37.04
E	61	2	0.5	248	33.7%	33.14

Fig. 9. Simulation results of public attitudes.

4.4. Simulating and decision analysis

(1) Response strategies setting

As shown in the stock flow diagram model (Fig. 7), the interactions among these system variables drive the evolution and diffusion of public sentiments and ultimately decide the results of the nuclear project by affecting the attitudes of the public. However, most of the variables, especially state variables, are uncontrollable from the perspective of government. Next, we chose the four controllable variables, *Times of government response*, *Response time of government*, *Degree of information transparency* and *Degree of popularity of nuclear knowledge*, to explore the effective response strategies for guiding the evolution of the public sentiment in this event. The series of different response strategies is shown in Table 3. The R0 strategy is the baseline strategy extracted from this real case; the other response strategies, including A1~A4, B1~B4, C1~C4 and D1~D4, are set with different specific values of the key control variables, respectively.

In this table, "Times of government response" represents how many times the government responds to public sentiment in an event. Its initial value is 7 (times), because in this case, 7 measures were taken to respond to the nuclear-related public sentiment event by the government. We tentatively adjusted its value from 1 to 70 to present the different strategies A1-A4. The number

of "Response time of government response" represents the time-delay in the government response processes. Its initial value is set to 2 (hours). We tentatively adjusted its value from 0.5 to 6 to represent the different strategies B1-B4. The "Degree of information transparency" values represent the disclosure degree of the nuclear project-related information. Its initial value is set to 0.5. We tentatively adjusted it from 0.1 to 0.9 to represent the different strategies C1-C4. The "degree of popularity of nuclear knowledge" value represents how the knowledge related to nuclear safety was popularized locally. Its initial value is set at 50.

The variables "degree of information transparency" and "degree of popularity of nuclear knowledge" are considered relative rather than absolute because they are hard to exactly quantify. Furthermore, our research focuses on reality testing (how the evolutionary trends of the public sentiment are simulated by the parallel cultivated SD model) and response strategies testing (how the evolutionary trends of public sentiment are influenced by different strategies). This consideration is reasonable. We can simulate the public sentiment scenarios and test the effectiveness of the improved response strategies by increasing or reducing their initial values.

(2) Simulation and discussion of strategy effects (response strategies testing)

After running the cultivated "7-generation Model" with different values of control variables for 300 h, the results indicate the corresponding effects of different strategies A1~D4 on public attitude to the nuclear project, respectively, and find the most appropriate response strategy for guiding nuclear public sentiment. The effects of the four controllable variables on public attitudes are shown in the in the two right-most columns of Table 3.

(3) The separate effects of the four control variables on public attitudes

Compared with the baseline scenario R0, the percentages of support posts under the control of strategies A3 and A4, respectively, rose to 7.37% and 21.36%. This means that the approval rating of the nuclear project will rise only by greatly increasing the "Times of government response", It is reasonable because the government is one of the project sponsors. Enhancing the measures of response and disposal by means of open information, popular science propaganda, and so on is helpful for increasing the approval

rating and guiding public sentiment in the right direction. This result also indicates that hypothesis 3 is tenable in this case.

Usually, the project approval rating increases as response speed or information transparency increases. However, the simulation results of the eight strategies from B1 to C4 show that the adjustments to the variables "Response time of government" and "Degree of information transparency" cause no obvious change in the public opinion. Therefore, these two variables are not the most important and Hypothesis 4, 5 is not entirely tenable in this case.

The percentages of support posts under the control of strategies D1 and D2 are, respectively, reduced to 2.63% and 3.73% from 5.56%; in addition, the percentages of support posts under the control of strategies D3 and D4 rise to 9.22% and 20.2% respectively. This simulated result obviously indicates that a lower "Degree of popularity of nuclear knowledge" by the public leads to a lower approval rating of nuclear projects. As the project was supported by government-owned corporations, this result also indicates that a higher "Degree of popularity of nuclear knowledge" leads to a higher controllable degree of nuclear project-related public sentiment. Professor Zhou also publicly declared that "the whole nuclear fuel processing in the Jiangmen base project does not relate to the nuclear fission reactions" (Li et al., 2015). However, due to the high threshold of nuclear technologies, it is very difficult for most people to quickly and effectively understand the safety of nuclear energy and accept nuclear projects. The blind worries regarding crises stemming from nuclear projects are one of the main reasons for triggering and spreading negative public sentiment and ultimately terminates potential projects. Therefore, spreading long-term and effective popular science propaganda about nuclear safety is necessary and important for the government to accumulate and improve the local degree of popularity of nuclear knowledge and ensure project success. Hypothesis 6 is therefore tenable.

Above all, adjusting the key control variables appropriately leads to completely different public attitudes and event results of the Jiangmen anti-nuclear mass incident. In the response processes, a higher approval rating of the nuclear project can be achieved using response strategies with higher degrees of response strength, response speed, information transparency and popularity of nuclear knowledge. The variable "popularity of nuclear knowledge" has the most remarkable effects on public attitudes than the other three variables. The approval rates ahead the disapproval rates leading to the project establishment only by appropriate increase (about six times as the initial value) of the "Degree of popularity of nuclear knowledge", These conclusions also indicate that only adjusting three other intermediate control variables, such as the "times of response" even up to ten times as the initial value, is still not enough to reduce the people's unreasonable fears and change the event result. The control variable "degree of popularity of nuclear knowledge" plays a decisive role in the evolution process of the public sentiment. However, it is not easy to increase the degree of popularity of nuclear knowledge in a short period of time. As an advance control variable, this indicator must be improved by education and advocacy activities for months or even years before the nuclear related public sentiment event actually occurs.

(4) The effects of the flexible combination strategies on public attitudes

Additionally, some flexible combination strategies adjust two or more control variable values at the same time, such as strategy E with the higher "times of government response" and "degree of popularity of nuclear knowledge", These strategies are better than the strategies adjusting only one control variable value once for guiding the public sentiment. Therefore, the evolution trend of the variable "quantity of support posts" impacted by the combination
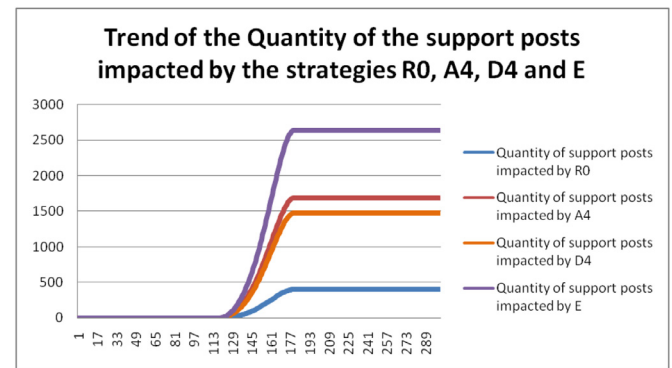
Fig. 10. Comparisons among the evolution trends of the variables "quantity of support posts" impacted by the various strategies R0, A4, D4 and E.

strategy E is compared with the trends impacted by the strategies R0, A4 and D4 respectively in Fig. 10. The comparison shows that the quantity of support posts increases significantly with the strategy A4 (much more times of government response) or the strategy D4 (much higher degree of popularity of nuclear knowledge). However, it can be seen in Table 3 that the percentages of support posts are still lower than percentages of support posts with the two single strategies separately in the end of simulation. However, the comparison also shows that the quantity of support posts increases much more significantly and rapidly using strategy E rather than A4 or D4. It can also be shown in Fig. 12 that strategy E leads to a higher percentage of support posts than percentage of opposite posts, which presents a reversed public sentiment simulation result that the approval rating is higher than disapproval rating for this nuclear-related project. Therefore, the government is able to guide and control the evolution and development of public sentiments more effectively in such a scenario by using the combination strategies.

Taking the anti-nuclear mass incident as a case study, the parallel simulation models of public sentiment regarding the incident are constructed and improved into the final realistic model gradually and iteratively, and the 18 different strategies for responding to real scenarios are simulated with the improved model to discover the effects of the control variables on public sentiments and provide relevant policy implications. The empirical research verifies the effectiveness of the PERDFPS framework and shows that the methods proposed in this paper can be very useful in providing decision support for guiding and controlling public sentiments during future nuclear energy developments.

5. Conclusions

5.1. Theoretical discussions

Traditional SD and PCM are integrated into the PERDFPS framework to solve the unconventional and unrepeatable public sentiment decision-making problems without any sufficient historical data in this paper. The novel approach cultivates the models to simulate real scenarios with real-time data rather than historical data in a parallel way.

Compared with the data-dependent "predict – response" decision-making methods, the structure-dependent "scenario – response" PERDFPS framework has more advantages. First, the parallel evolution and response mechanisms of the public sentiment are both considered in the iterative model-improving processes to achieve the consistency between the simulation results and the real scenarios. Second, in the case of a lack of historical data, the decision-making model can be constructed and cultivated gradu-

ally in the parallel-improving processes if the initial structure of the public sentiment system is describable. Moreover, the effects of various response strategies can be simulated and optimized by adjusting the key control variables of the cultivated model. It would be helpful for the government to enact better policies or decisions in future public sentiment events.

5.2. Limitations and future studies

The parallel interactions between the real scenarios and simulation models will be truly achieved and the decision effectiveness of the PERDFPS framework will be completely verified in the practical evolution and response processes of the public sentiments. However, due to the limited conditions (most original events such as nuclear-related large-scale project occur rarely), it is impossible to develop a simulation experiment according to a real-time scenario of a nuclear public sentiment in this paper. This research aims to propose the basic parallel decision-making framework to help governments guide and control public sentiment. Thus, the empirical research component of this paper uses the historic case of the Jiangmen anti-nuclear mass incident to demonstrate and discuss the principle and effectiveness of the PERDFPS framework.

Meanwhile, in order to carry out concise empirical research, details are not completely considered as the key variables of the multi-generational parallel simulation models. Therefore, in the next step, more elements, features, and other details of public sentiment systems, such as opinion leaders and their impacts on the public sentiment, should be designed and simulated to make decision-making models more realistic and effective in practical response processes. Furthermore, due to the similarity of the system structures, the novel approach can be used in the public sentiment events not only in the nuclear related field but also in many other fields, such as food safety and healthcare. Once events break out, the public sentiment systems can be constructed rapidly using little initial data and improved on iteratively and dynamically with real-time data. Using this framework, decision makers are able to describe, rehearse and make the proper decisions to guide or control the evolution trends of the public sentiment effectively. Therefore, in future studies, the PERDFPS framework and the relevant SD models can be extended to some other social heat incidents with similar public sentiment system structures such as "vaccination scandals" and "food-safety scandals",

Acknowledgments

Appendix A. the detailed description of minimum and preferred documentation

The following eTable 1 (Table 4) clearly explain all the variables defined in our models. The variables of the SD model are classified into two categories including state and control variables. And the latter is classified into two subcategories including parallel cultivating control and decision-making control variables. Each kind of variables has relevant functions in the model.

① The state variables are used to show the current state and evolutionary trend of the public sentiment system. Most of them are uncontrollable directly from the perspective of government such as "Increment of posts" and "News increment".

② The parallel control variables including "Increase rate of posts" and "Increase rate of news" are used to cultivate the n-general SD model. The key state variable "Increment of posts" is directly decided by the real-time state variables "Heat rate of public sentiment", "Reaction time of netizens" and the parallel control variable "Increase rate of posts". As shown in the rewritten Section 4.3, the variable "Increase rate of posts" of the initial 1-genernal SD model ($\triangle t = 60$ h) is defined temporarily as the formula (22) by collecting and fitting the 216 h of data (from July 17 to August 3, 2018) of similar public sentiment triggered by a similar event from ef.zhiweidata.com. And the formula (22) is finally adjusted into the formula (24) for the cultivated 3-general model ($\triangle t = 180$ h) after parallel iterative cultivating.

③ The decision-making control variables including "Times of government response", "response time of government", "Degree of information transparency" and "Degree of popularity of nuclear knowledge" are controllable from the perspective of government. These variables can be tentatively set by the decision makers to represent different response strategies. And then the effects of different strategies can be tested by reviewing the simulation result with the cultivated n-general SD model and the optimal strategy can be obtained by adjusting the control variables.

eTable 1
The detailed description of minimum and preferred documentation

Variables and Equations with comments

① State variables

News increment

= *Increase rate of news * 0.02 * Heat rate of public sentiment * source event* (1)

Unit: Item, Initial value: 0,

The *New increment* is the actual news increment per hour (step). The *Increase rate of news* is a variable derived from the statistic fitted curves in a similar public sentiment case (Zhang, 2012). The source event is Boolean. Its value equals 1 if the source event is trigged. It is affected by real-time heat rate of public sentiment. To normalize the *heat rate of public sentiment,* it should have been multiplied by 0.01. If we do this, the *News increment* will become only half of the real value of the case. Therefore, the parameter 0.02 is multiplied to it to keep the increment consistent with reality. In this way, the new increment changes follow the evolutionary rule of a similar case as well as the influence of the real-time heat rate of public sentiment.

Participation degree of media

= *100-95.26 * EXP (-0.000422 * Quantity of news)* (2)

Unit: Dimensionless, Initial value: 0,

This variable is a representation of media's extent of participation and concern about the public sentiment event. It has a positive correlation with the quantity of news. See (Zhang, 2012) and (Yu Le-an, Li Ling, Wu Jia-qian, 2015).

Quantity of news

= *INTEG (News increment, 0)* (3)

Unit: Item, Initial value: 0,

It is the accumulation of the news increments.

Heat rate of public sentiment

= *0.165933 * Participation degree of government +0.5036 * Participation degree of netizens +0.330433 * Participation degree of media* (4)

Unit: Dimensionless, Initial value: 0,

This variable represents the heat rate of the online discussion triggered by the public sentiment event. It is affected by *Participation degree of government, Participation degree of netizens* and *Participation degree of media.* See (Yu Le-an, Li Ling, Wu Jia-qian, 2015) and (Zhang, 2012).

Increment of posts

= *DELAY1 (Heat rate of public sentiment * 0.02 * Increase rate of posts, Reaction time of netizens)* (5)

Unit: Item, Initial value: 0,

It is the actual post increment per hour (step). The *Increase rate of posts* is a variable derived from the statistic fitted curves in the similar public sentiment case (Zhang 2012; Yu Le-an, Li Ling, Wu Jia-qian 2015). It is affected by real-time heat rate of public sentiment. To normalize the *heat rate of public sentiment,* it should have been multiplied by 0.01. But if we do this, the *News increment* will become only half of the real value of the case. So the parameter 0.02 is used to multiply with it to keep the increment consistent with the reality. In this way, the new increment changes follow the evolutionary regular of the similar case as well as the influence of the real-time heat rate of public sentiment. Furthermore, one-step delay is set to represent the netizens' response time after they receive the news.

Participation degree of netizens

= *100 - 35.73 * EXP (-8.388e – 005 * Quantity of posts)* (6)

Unit: Dimensionless, Initial value: 0,

This variable is a representation of netizen's extent of participation and concern about the public sentiment event. It has a positive correlation with the quantity of posts. See (Zhang, 2012) and (Yu Le-an, Li Ling, Wu Jia-qian, 2015).

Increment of support posts

= *Combined effects of government response actions * 0.01 * Increment of posts* (7)

Unit: Item, Initial value: 0,

The variable describes the support part of the post increment per hour. It is the product of increment of posts and the normalized combined effects of government response actions. The stronger effect of government response actions, the greater proportion of the increment of support posts, because government was the supporter of the project (Tian, 2011).

Increment of opposite posts

= *Degree of panic * Increment of posts* (8)

Unit: Item, Initial value: 0,

The variable represents the opposite part of the post increment per hour. The stronger degree of panic, the greater proportion of the increment of opposite posts. So, increment of opposite posts is the product of increment of posts and the degree of panic. See (Tian, 2011). We don't have to normalize the degree of panic because its value is between 0 and 1.

Increment of neutral posts

= *Increment of posts - Increment of support posts - Increment of opposite posts* (9)

Unit: Item, Initial value: 0,

The variable represents the neutral part of the post increment per hour deducting the parts of support and opposite post increments.

Positive and negative effects of posts

= *(Quantity of support posts - Quantity of opposite posts) / (Quantity of support posts + Quantity of opposite posts)* (10)

Unit: Dimensionless, Initial value: 0,

This variable represents the relatively gap between the support and opposite voices for the nuclear-related project from perspective of post quantity. Its value is between -1 and 1. And the greater Positive and negative effects of posts, the more supporters (Tian, 2011).

Degree of viewpoint collision

= *(2 * Quantity of opposite posts * Quantity of support posts) / (Quantity of opposite posts * Quantity of opposite posts + Quantity of support posts * Quantity of support posts)* (11)

Unit: Dimensionless, Initial value: 0,

The variable represents the difference between the support and opposite quantities. The less difference, the more balanced voices of both sides, and greater Degree of viewpoint collision– and vice versa (Tian, 2011).

eTable 1 (*continued*)

Variables and Equations with comments

Degree of panic

= *0.6 * (1 - Positive and negative effects of posts)+0.4 * Degree of viewpoint collision* (12)

Unit: Dimensionless, Initial value: 0,

The variable describes the degree of social panic. It has a negative correlation with *Positive and negative effects of posts* and a positive correlation with *Degree of viewpoint collision*. It means that more posts opposing the nuclear-related project heighten degree of panic. At the same time, the greater *Degree of viewpoint collision* regarding the public sentiment, the greater degree of panic. See (Tian, 2011).

Instantaneous quantity of posts

= *Increment of posts-Increment of opposite posts-Increment of support posts-Increment of neutral posts* (13)

In this case, the *Increment of posts* is calculated before the different types of post increments including *Increment of support posts, Increment of opposite posts* and *Increment of neutral posts* are separated and worked out according to the specific proportion decided by *Combined effects of government response actions* and *Degree of panic*. However, it is unavailable to connect the flow variable *Increment of posts* with the other flow variables *Increment of support posts, Increment of opposite posts* and *Increment of neutral posts* directly when modeling. Therefore, the stock variable *Instantaneous quantity of posts* created as mediation has no practical function except to connect the four flow variables to capture the different types of increments.

Quantity of support posts

= *INTEG (Increment of support posts, 1)* (14)

Unit: Item, Initial value: 0,

The variable represents the accumulation of the support post increments.

Quantity of opposite posts

= *INTEG (Increment of opposite posts, 1)* (15)

Unit: Item, Initial value: 0,

The variable represents the accumulation of the opposite post increments.

Quantity of neutral posts

= *INTEG (Increment of neutral posts, 1)* (16)

Unit: Item, Initial value: 0,

The variable represents the accumulation of the neutral post increments.

Quantity of posts

= *Quantity of support posts+Quantity of opposite posts+Quantity of neutral posts* (17)

Unit: Item, Initial value: 0,

It is the sum of quantity of support posts, opposite posts and neutral posts.

Increment of government response

= *DELAY1(MAX(0, Average degree of government response), Response time of government)* (18)

Unit: Item, Initial value: 0,

The increment of government response is decided by the average degree of government response. At the same time, there is a delay time to trigger it because of the response time of government.

Quantity of government response

= *INTEG (Increment of government response, 0)* (19)

Unit: Item, Initial value: 0,

It is the accumulation of the increment of government response.

Average degree of government response

= *Times of government response*50/180* (20)

Unit: Dimensionless, Initial value: 0,

This variable means average degree of government response measures per hour. As shown in Table 2, government took 7 measures to respond to the nuclear-related public sentiment event in this case. The concrete relationships between each measure and its influence are too complicated to be determined precisely. However, the *Average degree of government response* is simply a key variable for guiding the public sentiment in this example. We can perceive the evolutionary trend of the public sentiment and verify the principle and effectiveness of the proposed method by adjusting it. Therefore, the variable is considered as relative rather than absolute. The degree of each response measure is set to 50. The *average degree of government response* (per hour) is defined as total degree of each response measure (Times of government response*50) divided by total evolution period (180 hours).

Credibility of government

= *Degree of information transparency*0.3+Times of government response*0.2-Degree of panic*0.3-Response time of government*0.2* (21)

Unit: Dimensionless, Initial value: 0,

The credibility of government, which reflects public acceptance on the government measures, is the precondition of effective guidance and control of public sentiment. Tian (2011) believes that the credibility of government is decided by government's measures and degree of information transparency. In this case, the variable *Credibility of government* has the positive correlations with *Degree of information transparency* and *Times of government response*. It has the opposite correlations with *Degree of panic* and *Response time of government*.

② **Parallel control variables**

Increase rate of posts

In the section 4.3 of this paper, the variable *Increase rate of posts* of the initial 1-generation SD model ($T_{Testing-1}=2\triangle t=48$ h) is defined temporarily in the equation below by collecting and fitting the 240 hours of data (from July 15 to August 3, 2018) of the similar public sentiment triggered by a similar public sentiment event from ef.zhiweidata.com.

Increase rate of posts =

MAX (0, - 3.64e-008*Time^5 + 2.55e-5*Time^4 − 6.41e-3*Time^3 + 6.64e-1*Time^2 − 2.32e+1)*Time + 1.84e+2) (22);

The equation of 1-generation model is adjusted into the following one of the 2-generation model ($T_{Improving-2}=2\triangle t=48$ h, $T_{Testing-2}=3\triangle t=72$ h) after parallel iterative cultivating.

Increase rate of posts=

MAX (0, - 1.5e-06*Time^5 + 1.8e-4*Time^4 − 7.7e-03*Time^3 + 1.4e-01*Time^2 −8.9e-01*Time + 1) (23);

eTable 1 (*continued*)

Variables and Equations with comments

Similarly, for 3-generation model ($T_{Improving} = 3\triangle t = 72h$),

Increase rate of posts = MAX (0, - 7.9e-8*Time^5 + 1.2e-5*Time^4 − 6.4e-04*Time^3 + 1.5e-02*Time^2 −6.8e-02*Time) (24);

For 4-generation model ($T_{Improving} = 4\triangle t = 96h$),

Increase rate of posts = MAX (0, - 3.1e-9*Time^5 + 1.1e-6*Time^4 − 1.4e-4*Time^3 + 7.2e-3*Time^2 −4.1e-2*Time) (25);

For 5-generation model ($T_{Improving} = 5\triangle t = 120h$),

Increase rate of posts = MAX (0, - 2.2e-8*Time^5 + 6.6e-6*Time^4 − 6.9e-4*Time^3 + 3e-2*Time^2 −4e-1*Time + 1) (26);

For 6-generation model, ($T_{Improving} = 6\triangle t = 144h$)

Increase rate of posts = MAX (0, 5.2e-8*Time^5 − 1.4e-5*Time^4 + 1.3e-3*Time^3 − 4.9e-2*Time^2 −7.9e-1*Time - 4) (27);

The equation of 6-generation model ($T_{Improving-6} = 6\triangle t = 144$ h, $T_{Testing-6} = 7\triangle t = 168$ h) is adjusted into the following one of the cultivated 7- generation model ($T_{Improving-7} = 7\triangle t = 168$ h, $T_{Testing-7} = 8\triangle t = 192$ h) after parallel iterative cultivating.

Increase rate of posts = MAX (0, - 9.4e-8*Time^5 + 3.6e-5*Time^4 − 4.7e-3*Time^3 + 2.6e-1*Time^2 −6.2*Time + 19) (28);

Increase rate of news
In the section 4.3 of this paper, the variable *Increase rate of news* of the initial 1-generation SD model ($T_{Testing-1} = 2\triangle t = 48$ h) is defined temporarily in the equation below by collecting and fitting the 240 hours of data (from July 15 to August 3, 2018) of the similar public sentiment triggered by a similar public sentiment event from ef.zhiweidata.com.
Increase rate of news

= MAX (0, MAX(0, -3.6e-008*Time^5 + 2.5519e-005*Time^4 - 0.00640692*Time^3 + 0.663903*Time^2 - 23.16*Time + 183.903) (29);

The equation of 1-generation model is adjusted into the following one of the 2-generation model ($T_{Improving-2} = 2\triangle t = 48$ h, $T_{Testing-2} = 3\triangle t = 72$ h) after parallel iterative cultivating.

Increase rate of news = MAX (0, 5.5e-8*Time^5 − 4.6e-6*Time^4 − 5e-5*Time^3 + 2.8e-3*Time^2 − 3.2e-2*Time); (30);

Similarly, for 3-generation model ($T_{Improving} = 3\triangle t = 72h$),

Increase rate of news = MAX(0, -5.1e-8*Time^5 + 9.4e-6*Time^4 − 6.1e-4*Time^3 + 1.6e-2*Time^2 − 1.3e-1*Time) (31);

For 4-generation model ($T_{Improving} = 4\triangle t = 96h$),

Increase rate of news = MAX(0, -4.2e-9*Time^5 + 9.3e-7*Time^4 − 6.6e-5*Time^3 + 1.4e-3*Time^2 − 8.7e-3*Time) (32);

For 5-generation model ($T_{Improving} = 5\triangle t = 120h$),

Increase rate of news = MAX(0, 1.6e-9*Time^5 - 3.3e-7*Time^4 + 3.1e-5*Time^3 - 1.8e-3*Time^2 + 4.4e-2*Time) (33);

For 6-generation model, ($T_{Improving} = 6\triangle t = 144h$)

Increase rate of news = MAX(0, 7.1e-9*Time^5 - 2e-6*Time^4 + 1.9e-4*Time^3 - 7e-3*Time^2 + 2e-1*Time - 11) (34);

The equation of 6-generation model ($T_{Improving-6} = 6\triangle t = 144$ h, $T_{Testing-6} = 7\triangle t = 168$ h) is adjusted into the following one of the cultivated 7-generation model ($T_{Improving-7} = 7\triangle t = 168$ h, $T_{Testing-7} = 8\triangle t = 192$ h) after parallel iterative cultivating.

Increase rate of news = MAX(0, -1.4e-8*Time^5 + 5.2e-6*Time^4 − 6.4e-4*Time^3 + 3.3e-2*Time^2 − 8e-1*Time - 6); (35);

③ **Decision-making control variables**
Times of government response
= CONSTANT
Unit: times, Initial value: 7,
This variable is defined as one of the four key control variables. It represents how many times the government responds to the public sentiment. We can guide the evolutionary trend of the public sentiment and verify the effectiveness of the proposed method by adjusting it in the decision-making processes. Its initial value is 7 (times), because 7 measures were taken by the government to respond to the nuclear-related public sentiment event in this case.

Response time of government
= CONSTANT
Unit: hours, Initial value: 2,
This variable represents the time-delay in the government response processes. It is defined as one of the four key control variables. We can guide the evolutionary trend of the public sentiment and verify the effectiveness of the proposed method by adjusting it in decision-making processes. Its initial value is set to 2 (hours). We can simulate the public sentiment scenarios and test the effectiveness of the improved response strategies by increasing or reducing the initial response time.

Degree of information transparency
= CONSTANT
Unit: Dimensionless, Initial value: 0.5,
This variable represents the disclosure degree of the nuclear project-related information. It is defined as one of the four key control variables. We can guide the evolutionary trend of the public sentiment and verify the effectiveness of the proposed method by adjusting it in the decision-making processes. Therefore, the variable is considered as relative rather than absolute. Its initial value is set to 0.5. We can simulate the public sentiment scenarios and test the effectiveness of the improved response strategies by increasing or reducing the initial value.

Degree of popularity of nuclear knowledge
= CONSTANT
Unit: Dimensionless, Initial value: 50,
This variable represents how the knowledge related to nuclear safety was popularized locally. It is defined as one of the four key control variables. We can guide the evolutionary trend of the public sentiment and verify the effectiveness of the proposed method by adjusting it in the decision-making processes. Therefore, the variable is also considered as relative rather than absolute. Its initial value is set to 50. And we can simulate the public sentiment scenarios and test the effectiveness of the improved response strategies by increasing or reducing the initial value.

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